

## 9: Field Geology/Processes

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The field geology/processes group examined the basic operations of a terrestrial field geologist and the manner in which these operations could be transferred to a planetary lander. We determined four basic requirements for robotic field geology: geologic context, surface vision, mobility, and manipulation. Geologic context requires a combination of orbital and descent imaging. Surface vision requirements include range, resolution, stereo, and multispectral imaging. The minimum mobility for useful field geology depends on the scale of orbital imagery. Manipulation requirements include exposing unweathered surfaces, screening samples, and bringing samples in contact with analytical instruments. To support these requirements we recommended several advanced capabilities for future development. Capabilities include near-infrared reflectance spectroscopy, hyperspectral imaging, multispectral microscopy, artificial intelligence in support of imaging, XRD/XRF, and rock chipping.

### 9.1. INTRODUCTION

The maturity of our geologic knowledge of bodies in the solar system varies dramatically. All the planets except Pluto, many of the satellites, and several of the smaller bodies have been imaged at resolutions of a few kilometers. Higher-resolution orbital imagery, as well as site-specific analytical data, are available for the Moon, Mars, and Venus. We have identified undocumented samples (meteorites) from the Moon, Mars, and some asteroids. The Moon is the only solar system body other than Earth on which studies approaching classical field geology have been conducted.

Planetary field geology, for at least the near future, will be conducted by robotic spacecraft. The goals of these field studies will vary depending on the planet or satellite. An overarching goal will always be exploration, discovering basic facts about worlds that are almost unknown. Much effort may be put toward providing ground truth for interpretations based on orbital imagery, for example, the extent of basin ejecta or the reality of massive flooding. Planetary field studies may be targeted to answer specific questions, such as the presence or absence of lake deposits or permafrost. Finally, field work will certainly be called upon to support sample analysis and return by selecting samples and providing geologic context. These goals illustrate both the similarities and the differences between planetary studies and classical field geology that has been developed for over 200 years on the Earth.

### 9.2. TERRESTRIAL FIELD GEOLOGY

Field geology comprises the sensory and cognitive methods used to examine and interpret materials and structures at

scales appropriate to outcrops at the Earth's surface. This scale is dominantly that of meters, but includes scans over distances as far as the horizon as well as close-up inspection. Extrapolation must be made to include the subsurface. These observations are synthesized to larger scales by correlating among outcrop-scale inferences, another cognitive step. Some of these inferences can be synthesized in the form of geologic maps and cross sections. The field geologist attempts to characterize rocks and their identifiable units, the nature of the contacts or gradations between them, their spatial relationships, their origins, their structures, and their histories. Choice is required in defining useful rock units, and is dependent on both the scale of observation and the purposes of the geologist. Geologic history comprises the formation of rocks and rock units themselves and subsequent changes, such as weathering, metamorphism, burial, folding, faulting, and erosion. The geologist has a purpose before starting field work, ranging from derivation of an overall geologic history to a detailed accounting of some particular feature.

For some inferences, information not obtainable (or only obtainable with great difficulty) in the field must be acquired. These include rock chemistry, petrographic character, ages, and isotopic measurements. Thus the field geologist commonly needs to select and remove small samples for later laboratory analysis. However, field geology is much more than a sample-collecting expedition. In some cases the sample collecting is for investigation of deep-seated characteristics and processes (rather than near-surface events), such as isotopic studies of magmas or their xenoliths for mantle investigations. In any case, geologic context and characterization are prerequisites.

The main sensory tool of the terrestrial field geologist is a visual one. This visual tool is largely cognitive, rather than simply sensory, and its use is learned. However, human evolution has had influences that do not include the distinction of rhyolite from basalt, nor dolomite from calcite. Thus the geologist's senses are expanded by including a hand lens and some chemical and mineralogical indicators such as acids and streak plates. A common piece of equipment is the hammer, used to obtain fresh unweathered surfaces that are diagnostic of rock type and to obtain samples for laboratory analysis. The human visual system uses only a small part of the electromagnetic spectrum. In some circumstances the field geologist may use equipment that expands that range into the ultraviolet or infrared.

The geologist needs to relate an outcrop to other outcrops and to its surrounding terrain, and therefore requires base maps or images, and some means of accurately determining positions. Orientation and means of measuring angles for dips and strikes are also needed. On Earth this is generally done with a compass.

The geologist has to record observations, selecting from an infinite input those features considered relevant for the study. Field geology, like good writing, requires critical thinking. Experience going back more than 200 years shows that field geology is an iterative process of observation, hypothesis, testing, and synthesis. How this can be accomplished by telepresence is a topic of continuing debate (*Spudis*, 1992).

### 9.3. PLANETARY FIELD GEOLOGY

The main objectives of planetary field studies mirror those of terrestrial field geology: (1) identification and distribution of geologic units; (2) discrimination between primary rocks, sediments, and secondary weathering products; (3) estimation of the distribution, size, shape, texture, deposition, and erosional features of solid rocks; (4) estimation of the distribution, texture, deposition, and erosional features of soils and weathering products; (5) estimation of the three-dimensional orientation of features and samples; (6) estimation of the local topography and slopes; (7) identification and characterization of tectonic features; (8) estimation of tectonic orientations and local stress fields; (9) identification of layered materials and stratigraphic sequences; (10) identification of temporal and spatial variations of surface features; (11) preselection of samples for detailed analysis and definition of their geologic context; and (12) comprehensive geologic studies including the interrelation between compositional and structural/tectonic features as well as comparisons among sample analysis, local landing site data, and regional orbital data.

A robotic field geologist on a planetary surface will require a number of basic capabilities: **Geologic context** is knowledge of the lander's location and its relation to features recognizable from orbit. **Vision** is the ability to return recognizable images of the local area to Earth. **Mobility** implies significant movement of a rover away from the landing site. **Manipulation** is the ability to physically handle samples. Our group has attempted to develop requirements in these basic areas for any planetary lander (Table 9.1).

### 9.4. MARS PATHFINDER—THE CURRENT STATE OF PLANETARY FIELD GEOLOGY

Robotic field geology on planetary surfaces is in its infancy. Mars Pathfinder, due to be launched in 1996, will be the first planetary mission to include, albeit at a minimal level, our four basic capabilities of geologic context, vision, mobility, and manipulation. The geologic context was determined from Viking orbital imaging, but will not be supplemented by descent imaging. The capabilities of the lander camera are close to those required by our group, though the Pathfinder camera is not sensitive to wavelengths as long as 2.5  $\mu\text{m}$ . The Pathfinder rover, named Sojourner, has minimal capabilities for field geology. It moves extremely slowly, and will probably cover only a fraction of the area that can be seen from the lander. The rover will carry an  $\alpha$ -proton-X-ray spectrometer that can produce semiquantitative elemental

TABLE 9.1. Requirements for robotic field geology.

<b>Geologic Context</b>	
Orbital imaging	100-m to 1-km pixel resolution
Descent imaging	10-m-pixel resolution
<b>Vision</b>	
Range	Infinity to centimeters
Local horizon	100 m
Resolution	1 mrad (10 cm at 100 m)
Stereo	Far field and close-up
Spectroscopy	UV-VIS-NIR to 2.5 $\mu\text{m}$ , optimized for specific local conditions
<b>Mobility</b>	
Minimum range	1–10 km (10 pixels of orbital imaging)
<b>Manipulation</b>	
Transport analytical instruments to samples or samples to instruments	
Expose fresh (unweathered) surfaces	
Screen samples based on chemistry or mineralogy	

analyses of the rocks and soil. Fresh surfaces may be exposed by scraping rocks with the rover wheels.

Mars Pathfinder represents a first step toward true robotic field geology. It will demonstrate both the current state of the art and the very real need for advancements in this area of planetary science.

### 9.5. ADVANCED CAPABILITIES TO SUPPORT FIELD GEOLOGY REQUIREMENTS

The field geology/processes group recognized that comprehensive planetary field geology studies will require significant advances over current capabilities. We strongly endorse the development of the following technologies to support the next generation of robotic planetary landers:

- ♦ near-infrared reflectance spectroscopy to 2.5  $\mu\text{m}$
- ♦ hyperspectral imaging
- ♦ multispectral microscopy
- ♦ artificial intelligence in support of imaging
- ♦ XRD/XRF
- ♦ rock chipping

#### 9.5.1. Near-Infrared Reflectance Spectroscopy to 2.5 $\mu\text{m}$

Visible and near-IR reflectance spectroscopy are important techniques for remotely determining and mapping the compositions of planetary surfaces (including the Earth). The subject is reviewed in various publications, e.g., *Goetz et al.* (1983), *Elachi* (1987), *Vane and Goetz* (1988), and *Pieters and Englert* (1993). To summarize, spectral properties ("color") in the near-UV and visible ( $\sim 0.35$ – $0.7 \mu\text{m}$ ) are generally controlled by crystal-field electronic transitions within transition series cations (most commonly Fe), electronic charge transfers between cations, and electronic charge transfers between cations and anions (*Burns*, 1970). Other

sources of color in this wavelength region include conduction bands and color centers. Further into the near-IR (0.7–2.5  $\mu\text{m}$ ), overtone absorptions of vibrational fundamentals begin to dominate reflectance spectra. Water, OH, various carbonates, and other salts have diagnostic signatures in the near-IR. An additional capability of near-IR sensing is its ability to “see through” thin layers of certain materials and analyze the material(s) underneath. Examples include thin ferric-oxide stains (e.g., *Buckingham and Sommer, 1983; Singer and Roush, 1983*).

Beyond 2.5  $\mu\text{m}$ , reflectance observations of planetary surfaces and their interpretations are increasingly complicated by signal contributions from thermal effects, both from the object observed and within the instrumentation itself. For these reasons, 2.5  $\mu\text{m}$  is a logical and productive long-wavelength limit for the type of compositional discrimination and identification tasks proposed here.

These diagnostic near-IR vibrational features are all beyond the range of human vision, and many are beyond the range of silicon detectors such as CCD cameras. The development of reliable near-IR detectors suitable for planetary landers is an important area for support.

### 9.5.2. Hyperspectral Imaging

The canonical ideal instrument for remote sensing is an imaging or mapping spectrometer (also called a hyperspectral imager) that obtains complete spectral information for every spatial pixel of an image. The practical value of such data has been well demonstrated with prototype airborne instruments studying the Earth (e.g., *Vane and Goetz, 1988; Farrand and Singer, 1991; Farrand et al., 1994*). In the past such instruments have been quite large and expensive, with inherently large data rates. Recent developments in hardware technology, however, have reduced the weight and size, while software technology has also advanced to make these instruments more flexible and programmable. Special image compression software is being developed to manage the large flow of data.

The breakthrough in hyperspectral imaging is the ability to provide tens to hundreds of wavelength bands simultaneously for each pixel, whereas multispectral systems relying on filter wheels usually obtain no more than about a dozen bands. Since the spectral data are obtained simultaneously, there is no problem of co-registration of pixels taken with different filters at different times. The basic system passes light through a slit and onto a grating before illuminating a two-dimensional CCD array. In this manner, one axis of the array corresponds to the spatial dimension and the other to the spectral. The second spatial dimension of the image is obtained by scanning the slit across the scene in the direction orthogonal to the slit axis, thus producing an image “cube” with two spatial dimensions and one spectral dimension. In general, one can get hundreds of pixels in each of the three dimensions.

With this image cube stored in memory (either on the spacecraft or on the ground), one can now perform detailed analyses of the environment by searching for specific spectral

features. For example, the instrument can be programmed to search for the telltale absorption features of ferric oxides at 0.85–0.9  $\mu\text{m}$  and highlight their presence in the image. In current systems, the spectral resolution is 5–10 nm, which allows one to distinguish among mineral types with similar reflectance spectra. The high programmability of the instrument lends itself to data processing on board to lessen the amount of data downlinked. The processed data can be made to consist of a false-color image tinted according to mineral type.

A hyperspectral imager on a planetary lander will be able to achieve all and more of the science objectives normally associated with conventional imaging systems. A hyperspectral image of a landing site would enable investigators to efficiently select interesting locations, based on their mineralogy, for close-up examination and retrieval of samples by a rover. The stratigraphy exposed in a vertical surface would be readily discernable by the different spectral characteristics of each layer. Hyperspectral imaging would also enhance the information in geologic maps of a landing site by correlating morphology and topography with mineralogy.

The hyperspectral imager that will be flown on the Lewis spacecraft has the capability of imaging in 384 bands between 0.4 and 2.5  $\mu\text{m}$ . This instrument has a mass of 21 kg and a power requirement of 75 W. A smaller and simpler instrument called the Ocean Color Sensor (OCS) will fly on a Korean satellite and has a mass of only 6 kg. The OCS requires 20 W, but only images in 64 spectral bands between 0.4 and 1.0  $\mu\text{m}$ . Both instruments employ the orbital motion of the spacecraft to obtain the second spatial dimension. (An analogous system on a lander would require a scanning mechanism.) This technology continues to evolve and will undoubtedly become a standard tool of planetary exploration.

### 9.5.3. Multispectral Microscopy

Our understanding of the evolution of the Earth, Moon, and meteorite parent bodies has increased enormously due to sample studies at the millimeter to submillimeter scale. Evaluation of rock textures and mineral particles, their shapes, sizes, and distributions are critical to interpreting processes acting on planetary surfaces. Even without data on large-scale features, microanalytical studies have led to models of planet and asteroid formation, magmatic history, and interactions with the space environment. Petrologists, mineralogists, and experimentalists have developed criteria to identify processes such as magmatic crystallization, sedimentation, impact, and weathering through the studies of particle morphologies and compositions. A number of such criteria rely on the observation of rocks through hand lenses and microscopes. For loose samples, morphology and particle size distribution can often distinguish among impact, volcanic, eolian, aqueous, or evaporite origins. Rock textures, even at low resolution, indicate volcanic, plutonic, sedimentary, and metamorphic environments. Magmatic textures and compositions provide information on the nature of the source, ascent of the magma, and possible modification during emplacement.

A compact television microscope has been designed and constructed to obtain mineralogical and morphological information *in situ* on planetary surfaces (Jakeš and Wänke, 1993). This microscope can image an area of several square centimeters. The microscope uses a CCD chip and a TV camera, combined with lenses, mirrors, internal light, and fiber optics to image in visible, near-IR, or IR wavelengths. The magnification is changed by varying the optics. The best results have been obtained with magnifications of 10–100× on the TV screen, providing images with sufficient depth of focus and good resolution (better than 5  $\mu\text{m}$ ). The images can be digitized and saved to computer memory for later processing.

An internal “visible” light source has proven necessary for higher magnifications because the short working distance prevents sunlight from illuminating the area. Independent illumination allows the use of light of known spectral characteristics and sufficient intensity. With “white” light and color filters, multispectral images can be obtained. Multispectral images can also be obtained using monochromatic sources such as LEDs. Computer combination of images taken at different wavelengths can provide color images. Ultraviolet illumination providing “visible light” effects can be added to detect fluorescent phases. The use of near-IR or IR illumination enlarges the analytical capabilities.

The use of image processing makes the microscope camera an identification tool that can be used in planetary exploration (Jakeš, 1992). The value of mineralogical and chemical analysis increases if the analyzed object is “visually” known. It is imperative to exploration geology and geochemistry that analyzed surfaces are also imaged, at least in visible light.

A small microscope system has been designed for use in conjunction with  $\alpha$ -proton, X-ray fluorescence (XRF), and Mössbauer spectrometers (Rieder *et al.*, 1995). The microscope is built to image the same area as the chemical analyzer, approximately 40  $\times$  40 mm. In this system, the microscope camera can also image a smaller area (approximately 4  $\times$  4 mm) with resolution better than 10  $\mu\text{m}$  in order to identify mineral phases. Fixed focus optics connected to two chips and different color illuminations (0.470, 0.565, and 0.635  $\mu\text{m}$ ) are used. The size of the microscope camera system is 70  $\times$  40  $\times$  30 mm, and the weight is 150 g.

A microscope that provides mineralogical information together with reflectance spectra can be an extremely important tool for planetary field geology. Such an instrument offers the ability to directly correlate data collected *in situ* with those obtained by multispectral imaging through telescopes or from orbit.

#### 9.5.4. Artificial Intelligence in Support of Imaging

While multispectral remote sensing is usually thought of as measurements made from a great distance, similar observations can be equally important for near-field characterization of surroundings. Spectroscopic machine vision provides a wealth of compositional information compared with monochrome or three-color systems. The approach is to develop a

suite of practical capabilities for autonomous noncontact optical compositional determination in a spatial context, i.e., determining “what is it and where is it?”

Much, if not most, of the new work required to demonstrate such practical autonomous geologic exploration systems is in artificial intelligence and other software. The information returned from an autonomous sensor system should be a targeted, context-sensitive, high-level extract of the more voluminous data obtained by the system. This is true whether the recipient is another machine or a human. The sensor system must be able to adaptively decide what data to take, how and when to take it, and how to process and analyze it to suitably return the desired information about local geology. Such a system requires automated “intelligence,” onboard processing and analysis, and adaptive decision-making capabilities.

The real-world environments in which an intelligent spectroscopic imaging system needs to operate are intrinsically unstructured, and data collected will contain noise that can degrade the certainty of identification. After initial classification using multispectral image panoramas, the system must decide which image regions or cluster groups have classifications and/or identifications that are unacceptable and require spectral sampling. The decision that a cluster is unacceptable and requires new information must be based on the context in which the spectral data were taken, such as the complexity of the geologic setting, image acquisition parameters, and knowledge from previous spectral data. This information is often imprecise, vague, and uncertain.

Humans have the ability to make good decisions using this quality of information. Fuzzy logic seems to provide an ideal tool for transferring human decision knowledge into a computer-based control system, where decisions are made based on imprecise, incomplete, and uncertain information. A fuzzy-logic rule-based approach therefore seems an attractive avenue to explore in developing the necessary autonomous sensing systems. However, a number of such pilot systems must actually be built, tested, and rigorously assessed by geoscientists (who are understandably conservative when it comes to machines messing with their data) before the community at large can be expected to welcome (or even accept) such high levels of automation.

#### 9.5.5. X-Ray Diffraction and X-Ray Fluorescence (XRD/XRF)

In the field setting, a geologist automatically attempts to identify mineral suites in hand samples. In fact, this “suite recognition” (as opposed to recognition of individual minerals) is conducted mentally as a rapid-scan operation that subconsciously selects samples of interest while rejecting samples deemed irrelevant. It is a method of rapidly assessing samples that can be returned to a lab for more thorough analysis. If an instrument is to replace this human capability in robotic planetary exploration, the instrument should have the capability for both rapid assessment and intensive analysis. Given the requirements to identify mineralogy and select only a limited sample number for intensive study, there are

few instrument concepts currently available, particularly as field-deployable units.

A potential instrument concept that may satisfy this type of field requirement is a portable X-ray diffractometer capable of rapidly fingerprinting mineral suites. As depicted in Fig. 9.1, this concept utilizes a CCD detector and a multi-wavelength X-ray generator that enable Bragg angles to be satisfied for the detection of forward-scattered diffraction cones (a traditional single wavelength source will also suffice if placed close enough to the surface under investigation). Most noteworthy about such a design is the potential ability of the device to examine the rock or soil without the need to acquire or process a sample. Laboratory experiments (Marshall *et al.*, 1994; Keaten *et al.*, 1995) have indeed demonstrated that solid, rough-textured rock surfaces can be satisfactorily examined without powdering the samples for signal randomization.

The CCD can be interrogated for the position each photon strikes, thus providing diffraction information, or it can be interrogated for photon energy, thus providing elemental information via X-ray fluorescence. This combined XRD/XRF capability (Kerner *et al.*, 1995) enables geochemical augmentation of the diffractometric data, a capability that is particularly useful when there are complex mixtures of minerals or the presence of amorphous compounds with diffuse diffraction signatures. Certainly in the planetary exploration context, a technique such as XRD/XRF is needed to provide

calibration or "ground truth" for other analytical methods such as spectroscopic mineralogy or elemental analysis.

### 9.5.6. Rock Chipping

Planetary surfaces are exposed to myriad processes that alter the chemical and mineralogical nature of the topmost layer. On airless bodies, micrometeorites and solar wind atoms produce thin amorphous coatings of glass (patina) on exposed rock surfaces. On bodies with corrosive atmospheres like Mars (CO<sub>2</sub>) and Venus (SO<sub>2</sub>), thick weathering rinds may form. In order to measure the chemical and mineralogical properties of fresh rocks one has to first remove these altered surface layers.

An early version of the Mars minirover (Rocky IV) was equipped with a pecking tool run by a small cam (Fig. 9.2). As the rover drove up to a rock the pecking action chipped the surface much like a woodpecker until the wheels of the rover provided sufficient force to stop the pecking action. The rover then automatically backed up and started over. This sequence continued until the weathering rind was removed.

Another approach is the miniature rock chipper/sampler (MRCS), a reduced-size, lightweight version of a large rock sampler developed at the Applied Physics Laboratory (Cheng, 1994). The large rock sampler has demonstrated extraction and acquisition of 40-g samples from solid basalt rock, reinforced hardened concrete, and loose unconsolidated sand. The miniaturized version is designed to remove the weath-

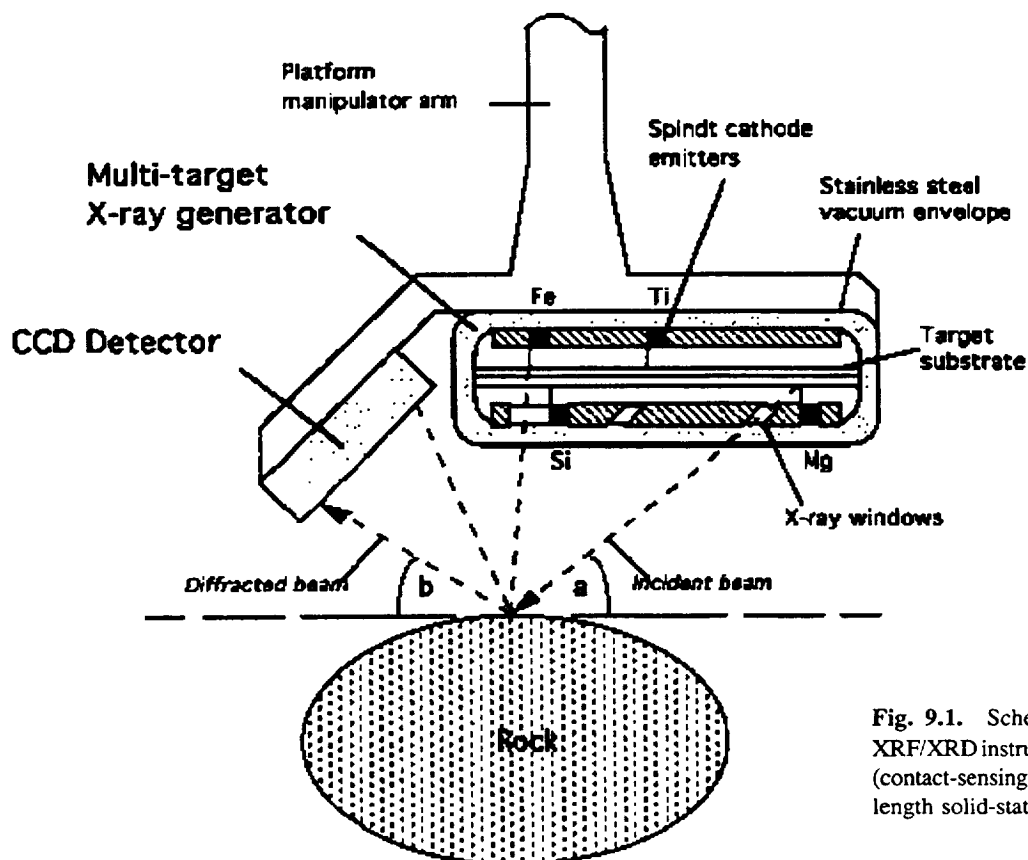
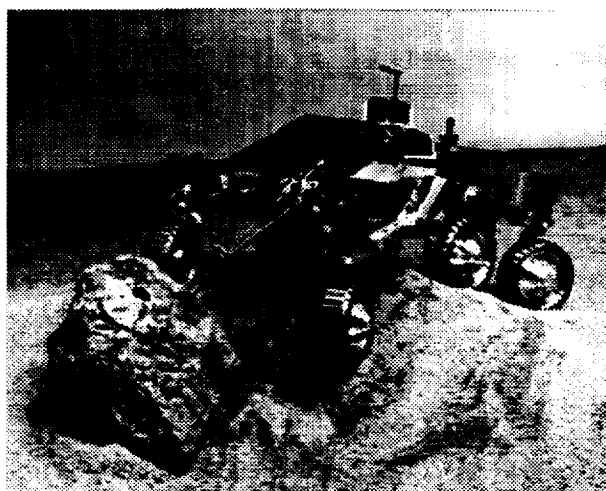


Fig. 9.1. Schematic design for combined XRF/XRD instrument based on a CCD detector (contact-sensing rock analysis using multiwavelength solid-state X-ray generator).



**Fig. 9.2.** Rocky IV illustrating the use of a rock chipper for removal of surface coatings (patina) from sample.

ered rind from a rock to allow access to the unaltered interior. It can also, as an option, collect small, separate samples of the rock, one sample containing weathered rind and the other containing rind plus interior material.

The MRCS uses a pyrotechnic device, similar to those used on spacecraft for cable cutters and bolt cutters, to drive a steel penetrator into the rock surface. The penetrator is retained within the MRCS and removed from the target surface after firing, and the propellant is vented away.

As a pyrotechnic device, MRCS operates rapidly, imposes no sustained force on the carrier vehicle, and has no sustained power requirement. It imposes a recoil and shock load on the carrier vehicle upon firing that is mitigated with appropriate shock mounting.

## 9.6. CONCLUSIONS

Planetary field geology, for at least the near future, will be conducted by robotic spacecraft. Basic requirements for robotic field geology include geologic context, surface vision, mobility, and manipulation. Geologic context requires a combination of orbital and descent imaging, with resolutions as fine as 10 m/pixel. Surface vision requirements include a local horizon at least 100 m from the lander, camera resolution of 1 mrad, stereo vision, and multispectral imaging in the ultraviolet, visible, and near-infrared. The minimum mobility for useful field geology depends on the scale of the orbital imagery, and ranges from 1 to 10 km. The robotic field geologist should be large enough to travel such a distance and tall enough to "see" geologic features in the area of interest. Manipulation requirements include exposing unweathered surfaces, screening samples, and bringing samples in contact with analytical instruments.

To support these requirements we recommend several advanced capabilities for future development. Capabilities include near-infrared reflectance spectroscopy to 2.5  $\mu\text{m}$ , hyperspectral imaging, multispectral microscopy, artificial intelligence in support of imaging, XRD/XRF, and rock chipping.

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